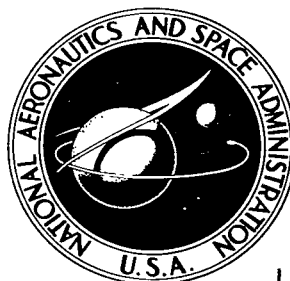


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SIMULATOR STUDY OF PRECISE
ATTITUDE STABILIZATION OF
A MANNED SPACECRAFT BY TWIN GYROS
AND PULSE-MODULATED REACTION JETS

by Armando E. Lopez and Jack W. Ratcliff

Ames Research Center

Moffett Field, Calif.

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SUMMARY

An automatic closed-loop system and a pilot-operated system were investigated with two different torque sources, a twin-gyro control system and a pulse-frequency-modulated reaction control system. These systems were evaluated on a large space-vehicle attitude-motion simulator.

The automatic closed-loop twin-gyro control system was able to maintain attitude about all three axes to within ± 1 second of arc. The response to step commands was rapid, and the system had good damping characteristics. The automatic closed-loop reaction control system was able to maintain attitude to within ± 3 seconds of arc. The dynamic response was not as rapid nor as well damped as the twin-gyro control system.

With either torque source, the pilot was able to stabilize the vehicle to within ± 5 seconds of arc of the desired attitude about all axes. When the gains in the rate feedback loop were at their highest value, the pilots considered the reaction control system slightly better than the twin-gyro system. The pilots commented that the control task required their undivided attention. With the twin-gyro control system, the pilots, generally, preferred a higher control power than with the reaction control system.

INTRODUCTION

During the midcourse phase of manned space flights while navigational sightings are being made, the attitude of the vehicle will have to be stabilized to some extent. The attitude limits and rate requirements of the stabilization system will depend on the navigational sighting equipment and the accuracy required. It may be desirable to stabilize the attitude of the vehicle to within a few seconds of arc to insure the accuracy needed to complete the mission.

One attractive means of controlling the spacecraft attitude is the use of twin-gyro controllers which act as torque sources. An advantage of this type of controller is that it eliminates the gyroscopic cross coupling inherent in a single gyro system, thereby allowing large gimbal angle deflections

so that most of the momentum stored in the gyros can be transferred to the vehicle. The elimination of cross coupling also permits the use of an independent control system about each axis. This facilitates the introduction of a pilot into the control loop. The large gimbal angles also improve the dynamic response characteristics of the control system. A complete description of the twin-gyro control system has been presented in reference 1. Also presented are some of the results of the automatic attitude control system. Some preliminary data with an automatic and manual attitude control system are presented in reference 2.

Another attractive approach is the use of an on-off reaction control system which is pulse frequency modulated. This system encompasses the reliability and simplicity of an on-off system with some of the handling qualities of a proportional control system. This proportionality in the control system facilitates the introduction of a pilot into the control loop.

Ames Research Center has investigated the use of both types of controllers. The two systems were operated automatically in a closed loop and manually by a pilot.

NOTATION

e_c	input signal to twin-gyro position servo
h	angular momentum of single gyro
H	angular momentum of vehicle
I_v	inertia of vehicle
K	gain constant
s	Laplace operator
t	time
T	torque output
$\Delta\omega_{jet}$	angular rate increment to the vehicle per pulse of reaction control jet
θ_c	angle of gyro momentum vector with respect to spin reference axis
τ	time constant, sec
ϕ, θ, ψ	attitude of the vehicle with respect to a laboratory frame of reference

VEHICLE SIMULATION

A sketch of the vehicle simulator with which these tests were conducted is presented in figure 1. This simulator is supported at the center by a ball and socket-type, low-friction air bearing. Measurements on the gas bearing support indicate that the combined friction and self-induced torques of the gas bearing support are in the order of a few hundred dyne-cm.

Figure 2 is a photograph of the space-vehicle attitude-motion simulator with some of the important elements indicated. Prior to each data run, the vehicle was balanced so that its center of gravity coincided with its center of rotation as accurately as could be determined. This was done to eliminate any static stability of the vehicle as well as constant gravity torques.

Although the pilot may control the attitude of the vehicle simulator from on board, as was done in the investigation reported in reference 3, in this investigation the pilot controlled the manual system from a fixed cockpit situated near the simulator.

TWIN-GYRO CONTROL SYSTEM

One of the twin-gyro controllers used as torque sources is shown in figure 3. The synchros were used as gimbal position sensors while the geared servomotors were used to position the gimbals. The construction of these controllers was based on the study reported in reference 4.

A twin-gyro controller is shown schematically in figure 4. The two gyros are shown as gimbals supported by a framework rigidly attached to a vehicle. With no input signal ($e_c = 0$) the gyros have their angular momentum vectors aligned along the spin reference axis but in opposite directions. For a given input signal, the gyros are forced to turn through equal and opposite angles, $\pm\theta_c$. The components of momentum along the momentum exchange axis add directly. The components of momentum along the other two axes cancel. The component of momentum about the momentum exchange axis is $H = 2h \sin \theta_c$ where H is the total momentum about the momentum exchange axis and h is the angular momentum of each gyro. The torque applied to the vehicle, through the framework, is the time rate change of momentum, $2h\dot{\theta}_c \cos \theta_c$.

Each twin-gyro controller had an angular momentum of about 110 million gm-cm²/sec or about 8 slug-ft²/sec. The servomotors were capable of a maximum gimbal angle rate of change, $\dot{\theta}_c$, of about 1 radian/sec. The resulting torque to the vehicle was therefore limited to about 8 ft-lb. The system generally operated at its maximum torque when responding to step attitude commands or disturbances.

The basic elements of a single-axis automatic twin-gyro control system are shown in the block diagram of figure 5. This system consisted of an attitude sensor (star tracker) signal processing circuit, gyro position servos,

gyro elements, and a vehicle. Three single-axis control systems were mounted on a space-vehicle attitude-motion simulator with the momentum exchange axes of the gyros mounted orthogonally for control about the three body axes of the simulator. The values of τ_1 , τ_2 , and τ_3 shown in figure 5 were 0.2, 0.015, and 0.2 sec, respectively. Other important details of the automatic twin-gyro control system including gains and time constants have been presented in references 1 and 2. With the gains used in the automatic closed-loop mode the lead term $(1 + \tau_1 s)$ was necessary to compensate for the lag term $(1 + \tau_3 s)$ in the gyro position servo.

External torques in the form of small jet reaction torques were applied to return the gyros automatically to their neutral position, $\theta_c = 0$, whenever the gimbal angle exceeded 60° . With the exception of gains and inertia values, the control systems about all three axes were identical.

The block diagram presented in figure 6 outlines the system with the pilot closing the loop. In order to assemble a manual control system, the basic elements of the automatic control system were modified to include the pilot in the loop. These modifications consisted of the introduction of a pilot controller and attitude display and the elimination of the lead-lag networks.

Preliminary runs were conducted with a pilot-operated system with and without the lead-lag network. The pilots expressed a slight preference for the system characteristics without this network. However, there was no apparent difference between the data with and without this network.

PULSE-MODULATED REACTION-CONTROL SYSTEM

The cold-gas reaction-control system was operated in a pulse-frequency modulated mode. Each pulse of the reaction control system had a constant time duration and imparted a constant incremental value of angular velocity, $\Delta\omega$, to the vehicle. The pulse frequency was a function of the error signal or the pilot's input.

Figure 7 shows a time history of input signal and thrust output of one nozzle for one pulse. The time delay was approximately 20 milliseconds. The time duration of each pulse was about 26 msec about the roll axis and approximately 20 msec about the pitch and yaw axes. This minimum pulse width was dictated by the dynamic response of the solenoid valves in the reaction control system. The minimum pulse width of 25 msec and the time delay of 20 msec restricted the maximum frequency to about 20 pulses per sec. (The minimum was chosen to be about 1 pulse per sec.)

The pulse width of about 20 msec combined with maximum and minimum pressure on the reaction control system limited the range of vehicle velocity increments per pulse from 0.6 to about 20 seconds of arc/sec.

A simplified block diagram showing the important elements of the automatic closed-loop reaction control system is presented in figure 8. The lead term, necessary for stability of the system, was supplied by rate gyros.

A block diagram depicting the manually operated reaction control system is presented in figure 9. The rate feedback gain was varied from 0 to about 5×10^5 volts/radian/sec for the manually operated tests.

ATTITUDE SENSOR

The attitude sensor for this investigation consisted of a set of two star trackers mounted off the vehicle and two light sources on the vehicle (see fig. 2). One sensor was mounted to the side of the vehicle for detecting roll attitude and the other sensor was mounted in front of the vehicle to detect yaw and pitch attitudes. These sensors had a linear output between ± 30 sec of arc.

ATTITUDE DISPLAY

The attitude of the simulator was displayed to the pilot as a horizon line on an oscilloscope (5 in. diameter) with a spike in the center (fig. 10). An attitude error of 5 sec of arc about the pitch axis displaced the horizon line vertically 1 cm; an error of 5 sec of arc about the yaw axis displaced the spike along the line 1 cm; and a roll error of 5 sec of arc rotated the line approximately 14° .

This display differed from a conventional artificial horizon in that the displacement of the horizon due to a pitch attitude error was in a vertical direction rather than normal to the horizon. This scheme was justified on the basis of the small-angle deflections in this investigation. The pilots commented that this system was appropriate for the control task involved.

PILOT CONTROLLER

The proportional controller shown in figure 11 was used in the pilot-operated control system. It consisted of a two-axis pencil-type controller for roll and pitch control and a set of toe pedals for yaw control. The characteristics of this controller system are shown in figure 12. The pencil controller was identical to that used in the investigation reported in reference 5. The characteristics of this controller were considered satisfactory by the pilots for control of an entry vehicle at high levels of acceleration. Since it would be desirable to have one controller for all phases of space flight, this controller was adapted for this investigation. Here again, the pilots considered this controller adequate for the control task.

RESULTS

Automatic Twin-Gyro Control System

The task for the automatic control system was to control the vehicle to as precise an attitude as practical and still maintain a reasonable dynamic response and damping characteristic.

The performance of the automatic control system is demonstrated by the time histories presented in figure 13(a) which demonstrate the ability of the automatic system to stabilize the attitude of the vehicle. Although no deliberate disturbances were introduced, the simulator was subject to random disturbances from circulation of air about the simulator. In spite of these random disturbances, the attitude of the vehicle was held to within ± 1 sec of arc. The response to a step command in vehicle attitude was rapid and, following the first overshoot, showed reasonable damping characteristics. Within a few seconds of time the vehicle was stabilized to within 1 sec of arc of the commanded attitude.

Step commands of vehicle velocity were introduced simulating disturbances caused by the occupant. Figure 13(b) shows a time history of attitude of the simulator while subjected to step commands in vehicle velocity of 10 sec of arc/sec for 1 sec of time. Step commands up to 100 sec of arc/sec for 1 sec of time were introduced without exceeding the ability of the twin-gyro system to stabilize the vehicle. The time to damp following large disturbances varied from 2 to 3 sec about the roll axis to 8 to 10 sec about the pitch or yaw axis.

Disturbances up to 100 sec of arc/sec represent a typical movement of an occupant in a vehicle the size of the Apollo. In a vehicle with about 14,000 slug-ft² inertia about the pitch axis, an occupant seated at the mass center would cause an attitude change of 20 sec of arc while moving his hands from an arm chair position to a position over his head, provided there were no attitude control system and no initial angular rate.

REACTION CONTROL

Automatic Closed-Loop System

A typical time history of attitude of the simulator while being controlled by a pulse-modulated reaction control system is presented in figure 14. In the absence of deliberate disturbances, the control system held the attitude of the simulator to within ± 3 arc sec of the commanded attitude about all axes. The response to the step command in attitude was rapid and, in about 4 seconds after the command input, the attitude was once again within ± 3 sec of arc of that desired. No simulated internal disturbances were applied to the simulator during the tests with the reaction control system.

Manual Twin-Gyro Control System

The pilot's task during these tests was to maintain the attitude of the vehicle to within ± 5 sec of arc about all three axes. After a 2-minute period of undisturbed flight, deliberate disturbances were introduced. The pilot's task was to return the vehicle to within ± 5 sec of arc about all axes as quickly as possible.

The majority of the data were obtained with a reserve military pilot who had about 850 hours of jet-flight experience. The remaining data were obtained with an engineering test pilot who had about 2,400 hours of jet-flight experience. The pilots rated the system as acceptable. However, they did comment on certain undesirable characteristics, namely, the absence of the vehicle static and dynamic stability generally present in aircraft. They stated that while the control task was not exceptionally difficult to perform, it did require their undivided attention.

The manual control system was tested under the same conditions as the automatic system with step commands in vehicle velocity simulating disturbances caused by the occupant. Figure 15 is a time history of vehicle attitude during a typical run with a manually operated control system. Although no deliberate disturbances were introduced for the first two minutes, the system was subject to minor disturbances due to air circulating about the simulator and random inputs by the pilot. It can be seen in this figure that the pilot could maintain attitude to within 5 sec of arc during the undisturbed portion of the flight. When the disturbances were introduced about one or two axes simultaneously, the pilot was able to return the vehicle to the prescribed limits rapidly.

Manually Operated Reaction Control System

The pilot-operated system was investigated with a variation in two parameters, the torque output of the nozzles and the feedback from the rate gyros. The range of torque output of the reaction control nozzles resulted in a range of vehicle angular rate increments per pulse of from 0.6 to 20 arc sec/sec. The range of rate feedback was from a maximum value of 5×10^5 volts/radian/sec to zero feedback. With maximum rate feedback, the maximum value of rate the pilot could command through his controller was about 40 sec of arc/sec. With zero feedback, the pilot theoretically could command an infinite rate.

A time history of attitude of the vehicle for a manually operated reaction control system is presented in figure 16. In this case the jet output was set at a value which corresponded to a velocity increment per pulse of about 12 sec of arc/sec and a maximum rate feedback. Without much difficulty the pilot could maintain ± 5 sec of arc about the commanded attitude about all axes.

Comparison of Twin-Gyro and Reaction Control Systems

The twin-gyro and reaction control systems were evaluated on the same simulator with the same attitude sensing equipment. The automatic twin-gyro control system was able to maintain vehicle attitude to within ± 1 sec of arc of the commanded attitude about all axes and still maintain good dynamic response. The automatic reaction control system was capable of maintaining vehicle attitude to within ± 3 sec of arc of the commanded attitude. No specific requirements have been established for attitude stabilization systems for manned space vehicles. However, the response and damping characteristics of both control systems are good. The twin-gyro control system had a basic frequency response of about 1 cps and damped to within 1/10 amplitude in one cycle. The time history of attitude presented in figure 14 shows that the damping characteristics of the reaction control system were such that within two cycles after the command input, the attitude of the vehicle was once again within ± 3 sec of arc of the desired attitude.

The pilots were asked to rate the control systems on the basis of ability to maintain an attitude error of less than ± 5 sec of arc about all axes and to return the simulator to within these limits following command changes or disturbances. Their opinions were in the form of numerical ratings based on the rating schedule presented in reference 6.

The pilots rated the twin-gyro control system with a range of gains in the pilot control loop. Since the pilot, through his controller, commands a gyro gimbal position which is equivalent to a vehicle angular velocity, it is appropriate to define the control system output in terms of vehicle angular rate. The range of maximum vehicle rate command was from about 50 to 400 sec of arc/sec. The pilots generally rated the system as unsatisfactory but acceptable for the task involved. The data are presented in figure 17. These data appear to indicate a preference for a control power of about 200 to 300 sec of arc/sec.

The pilots' opinion of the reaction control system is shown in figure 18. When the rate feedback gain was set at its highest value, thereby limiting the rate command to about 40 sec of arc/sec, the pilots rated the control system satisfactory. However, as the rate feedback was reduced, the pilots downgraded the system. In the absence of any rate feedback, the pilots rated all control powers as unsatisfactory. With the highest rate command, the pilots rated the reaction control slightly better than the twin-gyro control.

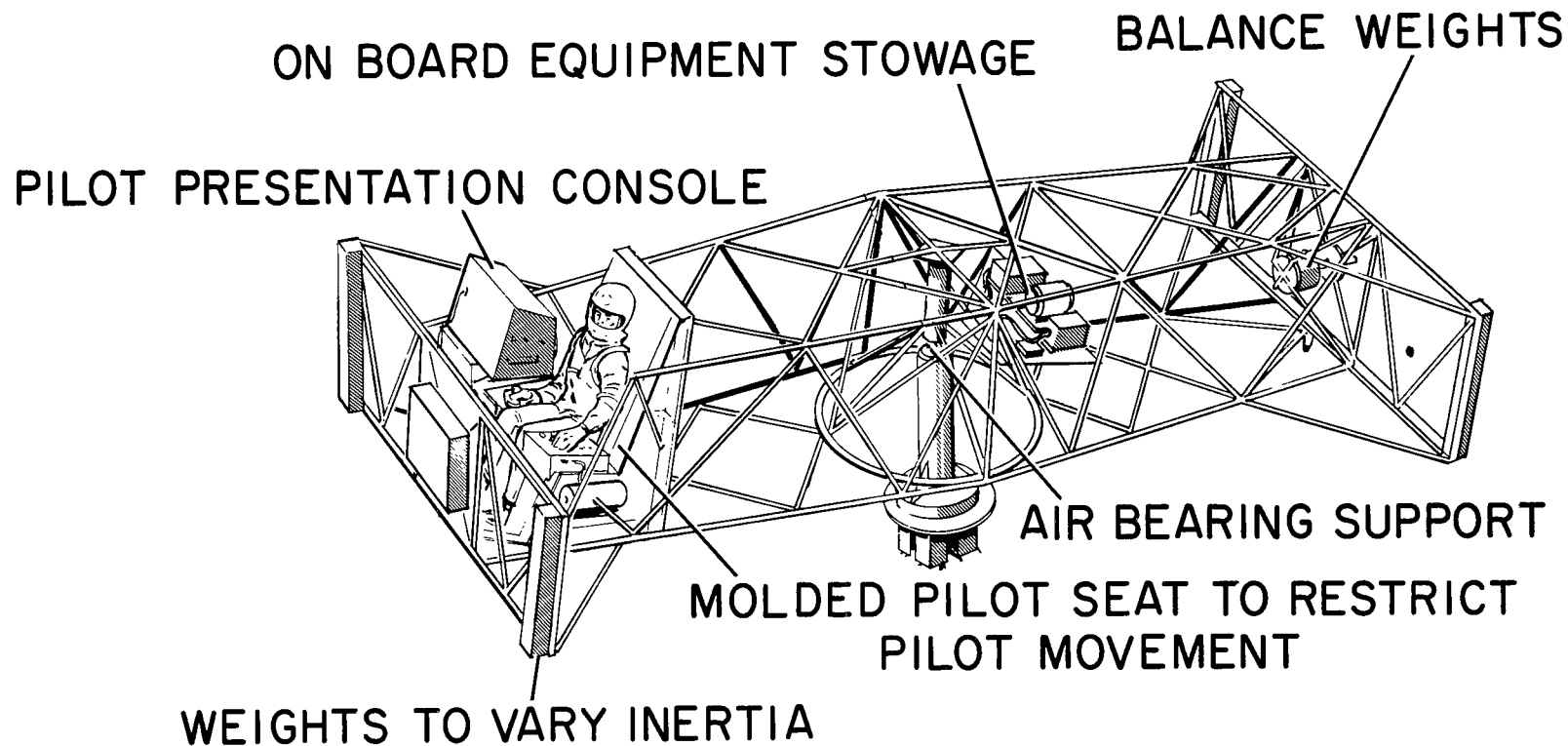
One subjective comment by the pilots was that while the control task was not extremely difficult, it did require their undivided attention. Generally, the pilots preferred a higher control power with the twin-gyro control system than with the reaction control system.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., July 10, 1964

REFERENCES

1. Havill, Jerry R., and Ratcliff, Jack W.: A Twin-Gyro Attitude Control System for Space Vehicles. NASA TN D-2419, 1964.
2. Lopez, Armando E., Ratcliff, Jack W., and Havill, Jerry R.: Results of Studies on a Twin-Gyro Attitude Control System for Space Vehicles. AIAA Paper 63-332, August 14, 1963.
3. Lopez, Armando E., and Smith, Donald W.: Simulator Studies of the Manual Control of Vehicle Attitude Using an On-Off Reaction Control System. NASA TN D-2068, 1963.
4. Amster, M. N., Anderson, R. P., and Williams, H. M.: Analysis of Twin-Gyro Attitude Controller; Final Summary Report. EL-EOR-13005, Chance Vought Aircraft, Inc., June 16, 1960.
5. Creer, Brent Y., Smedal, Harold A., and Wingrove, Rodney C.: Centrifuge Study of Pilot Tolerance to Acceleration and the Effects of Acceleration on Pilot Performance. NASA TN D-337, 1960.
6. Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aero. Eng. Rev., vol. 16, no. 3, March 1957, pp. 47-51, 56.





LENGTH 24 ft	I_{xx} 600 slug-ft ²
WIDTH 12 ft	I_{yy} 6,500 slug-ft ²
HEIGHT 4 ft	I_{zz} 7,000 slug-ft ²
WEIGHT 4,000	

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Figure 1.- Schematic view of space vehicle attitude-motion simulator.

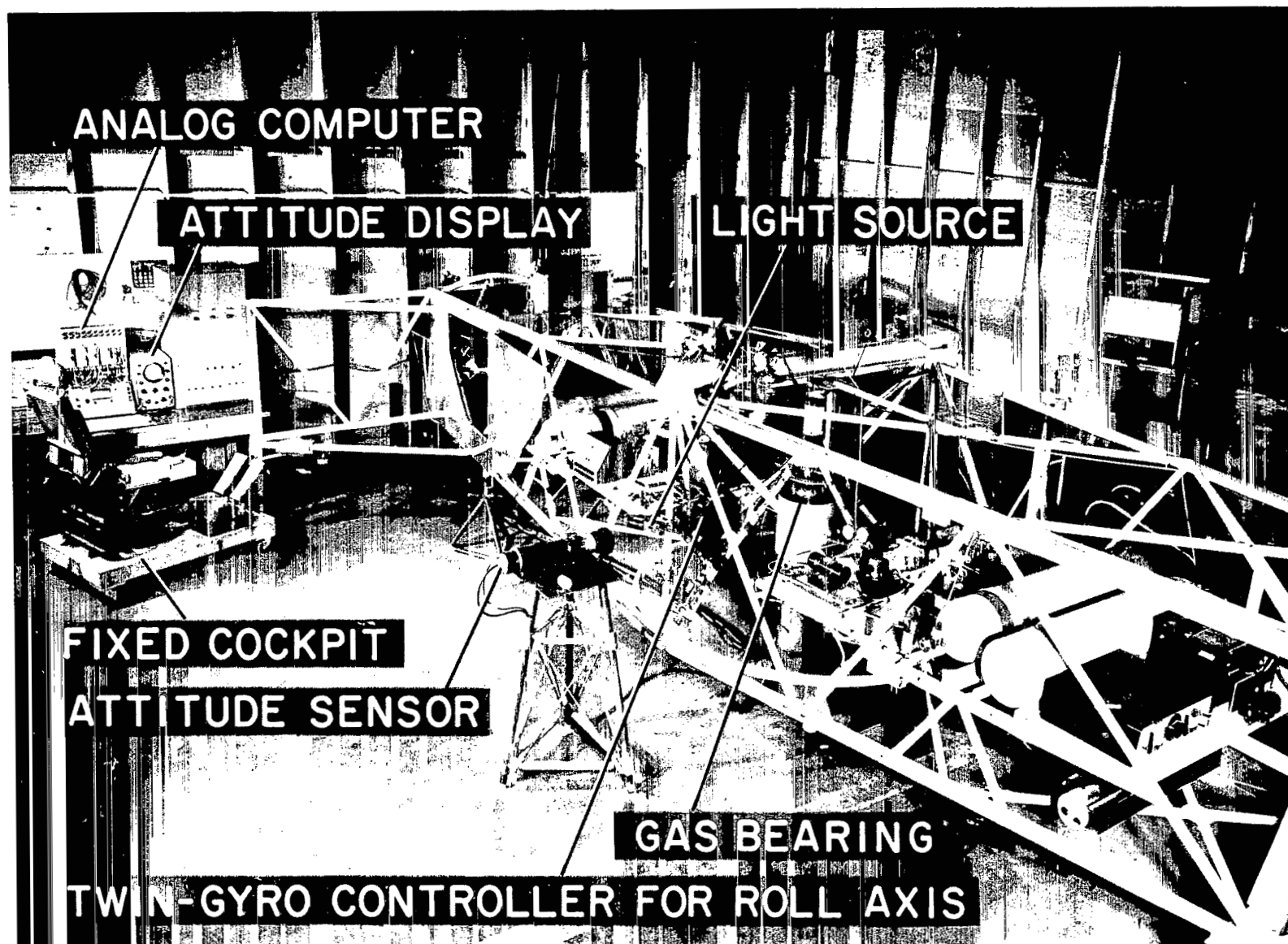


Figure 2.- Photograph of space-vehicle attitude-motion simulator.

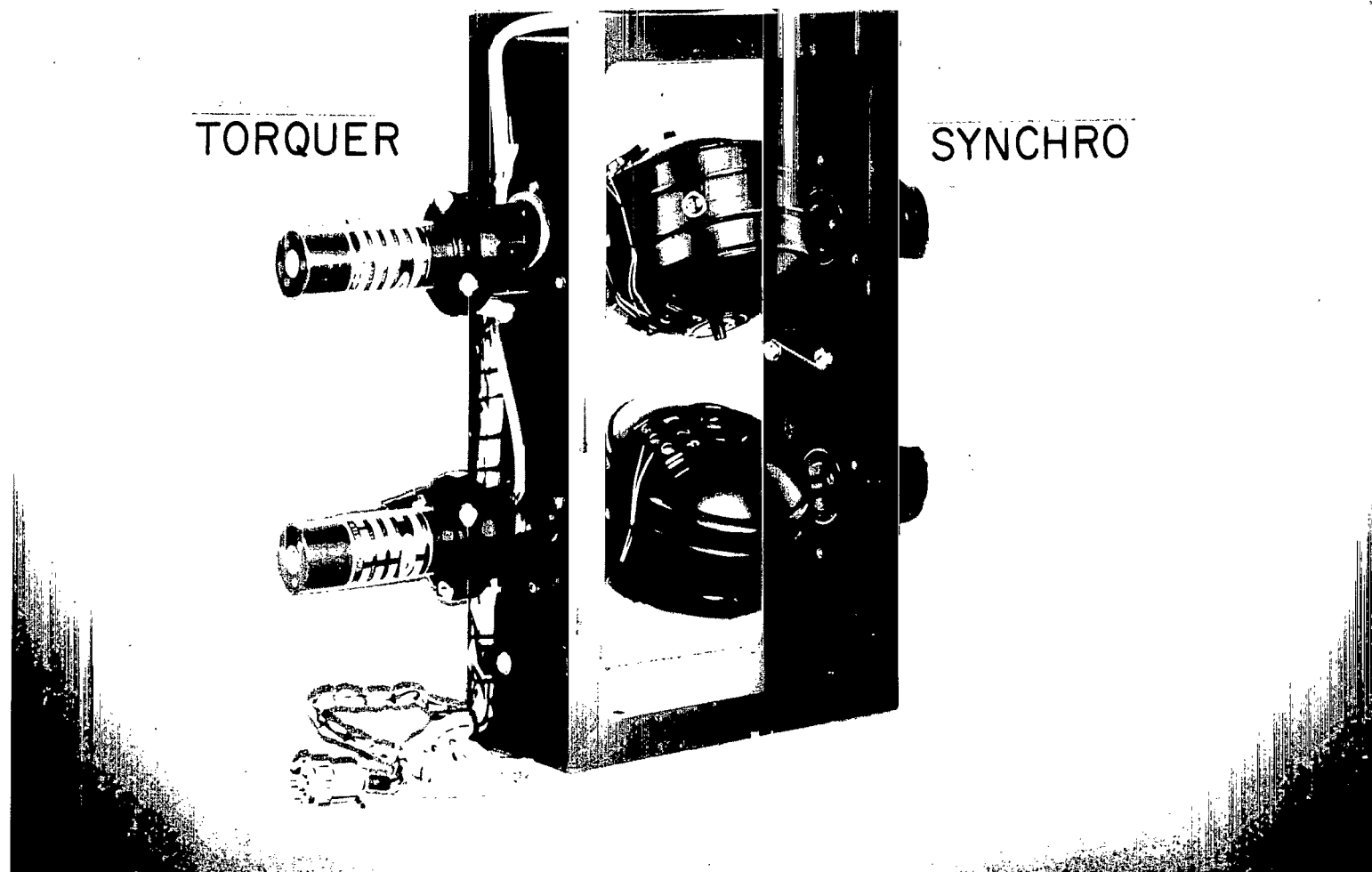


Figure 3.- Photograph of twin-gyro controller.

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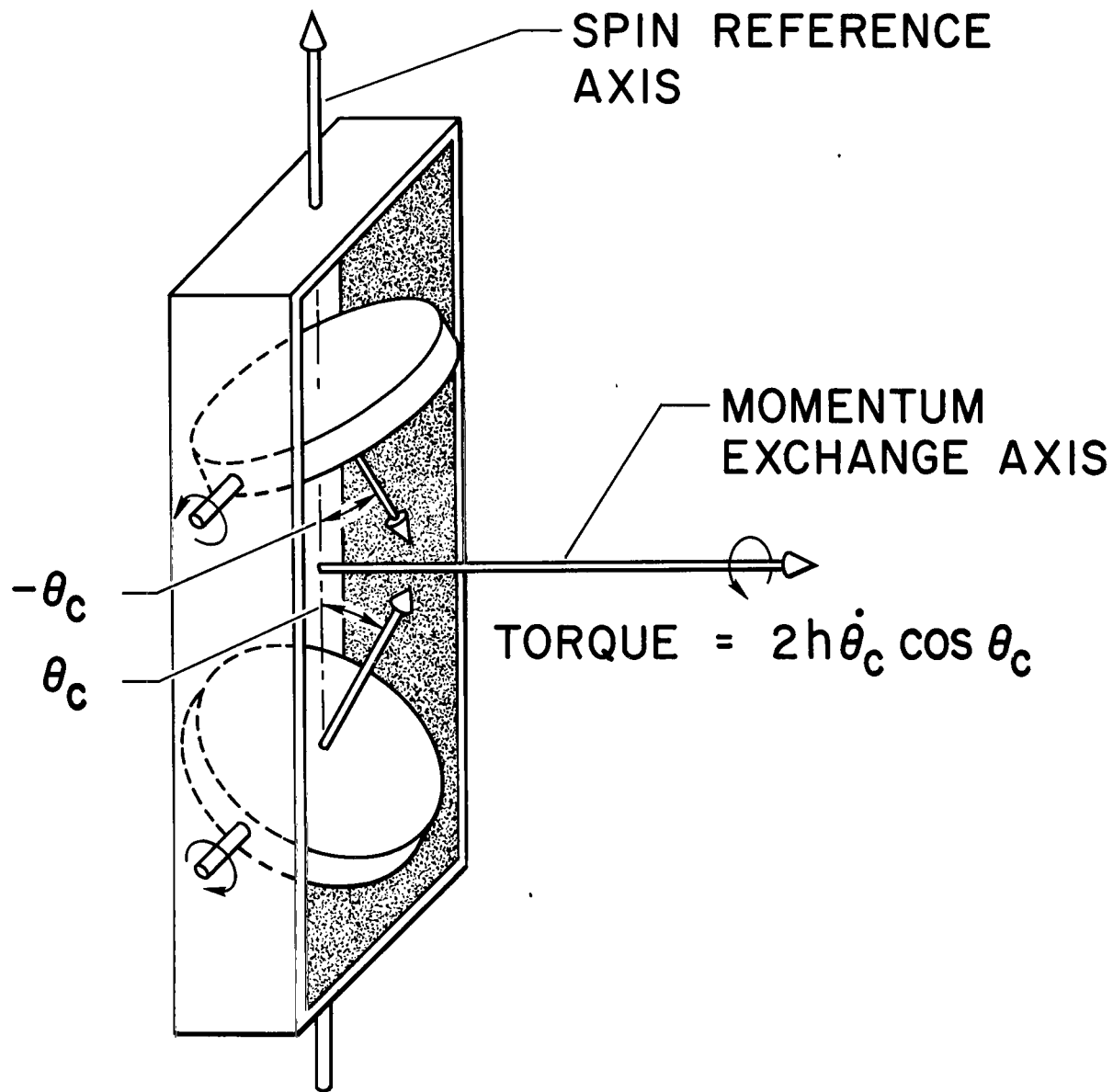


Figure 4.- Schematic view of twin-gyro controller.

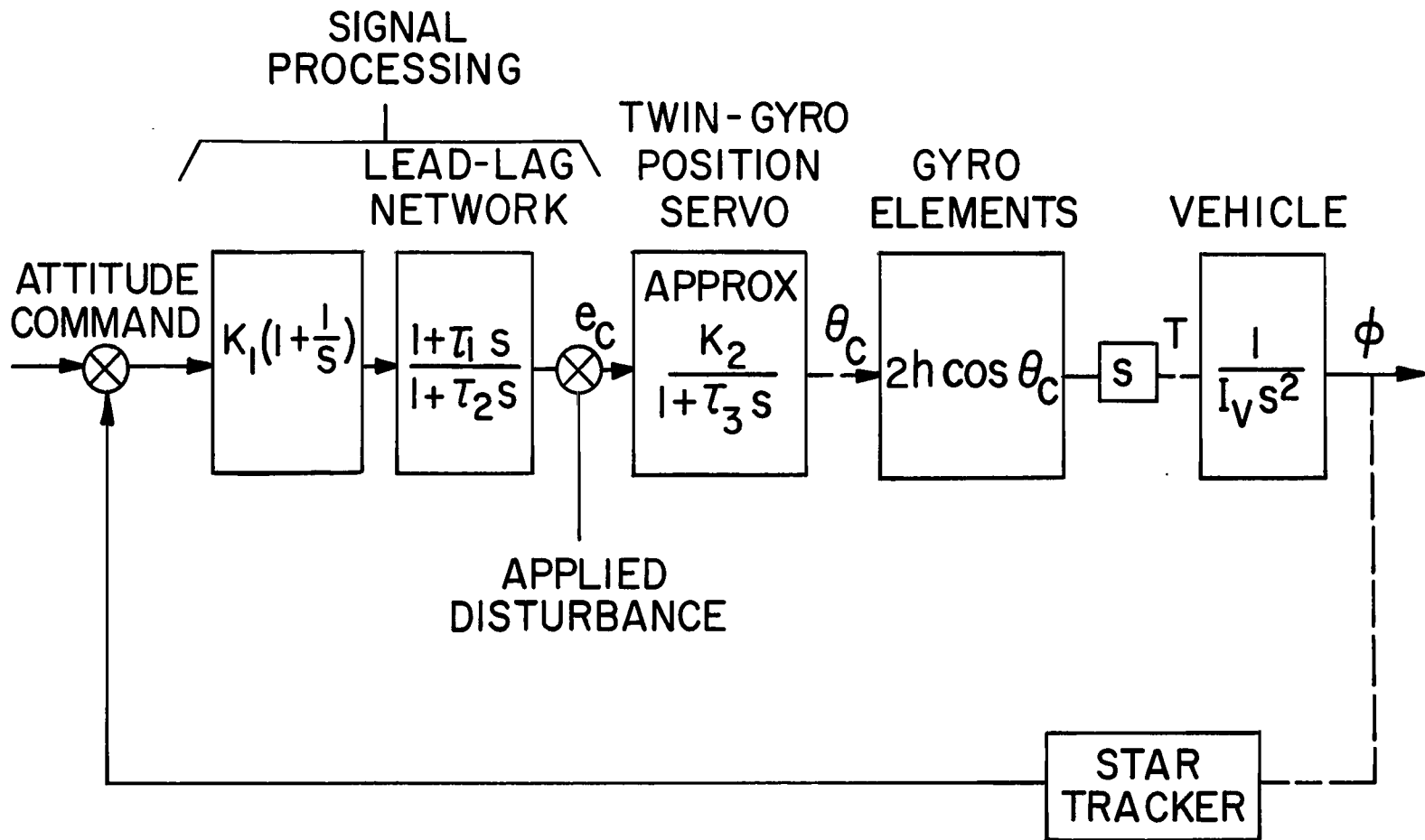


Figure 5.- Block diagram of the automatic twin-gyro control system.

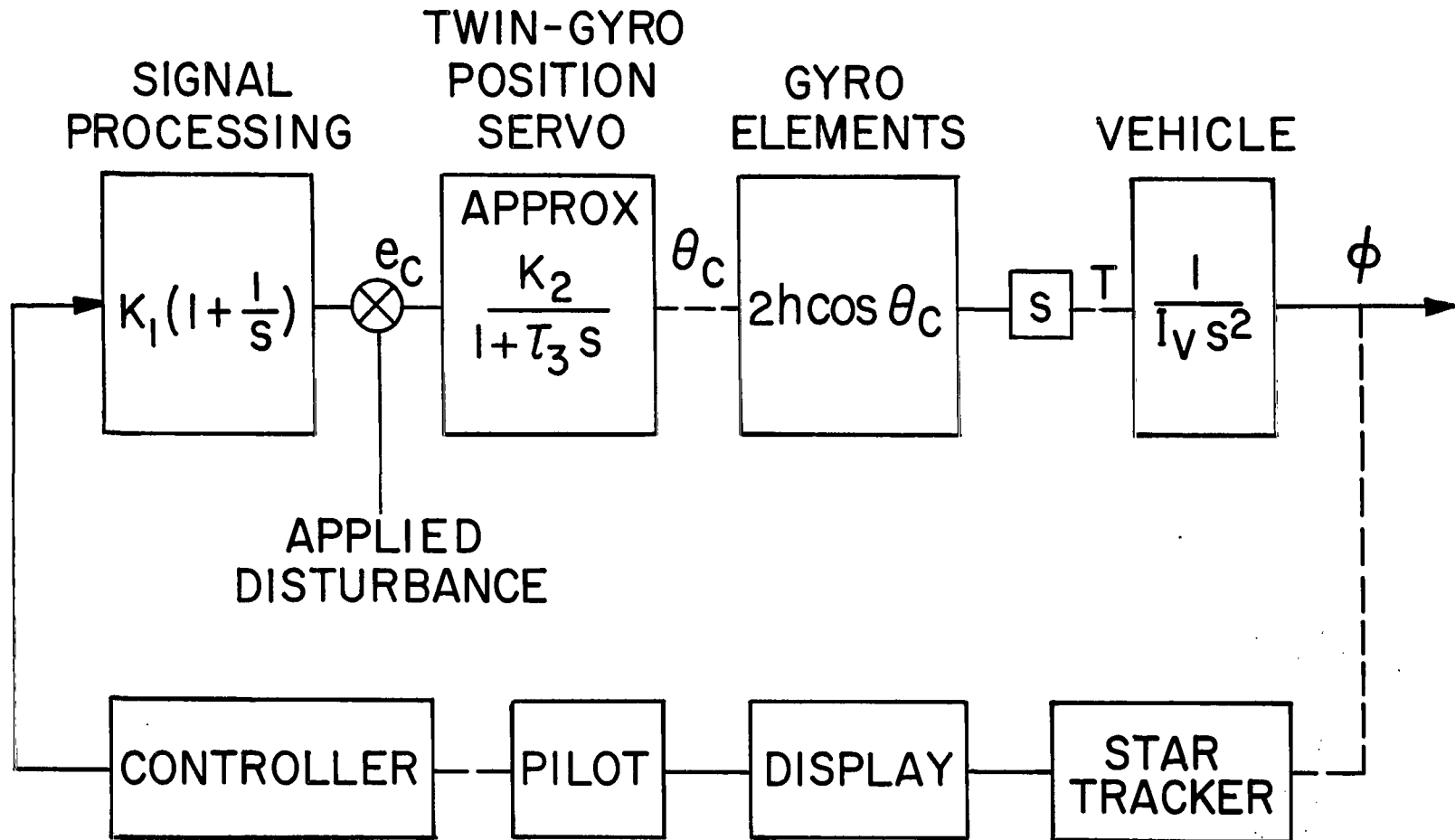


Figure 6.- Block diagram of the manually operated twin-gyro control system.

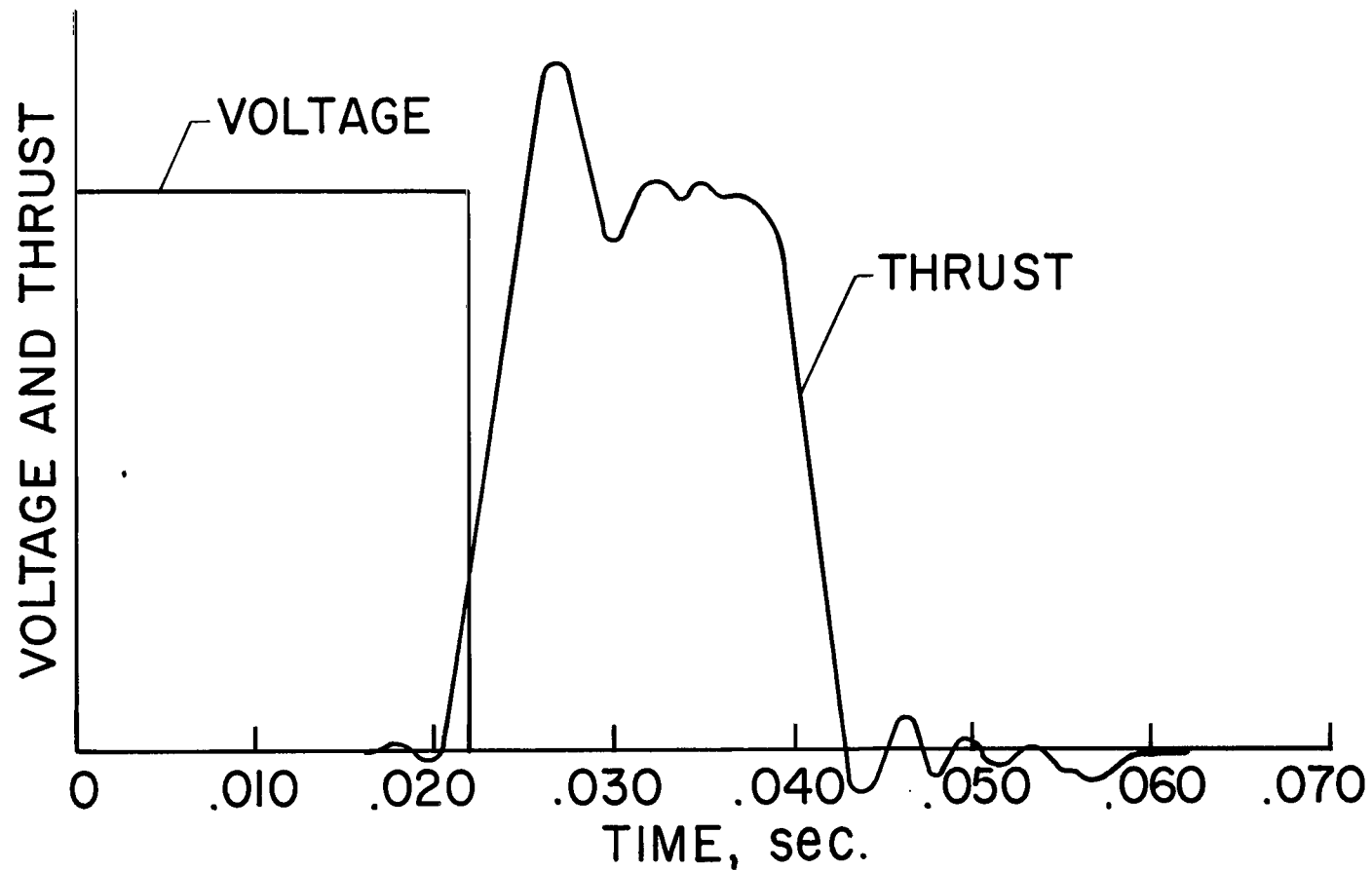


Figure 7.- Time history of input signal and thrust output of one nozzle for one pulse.

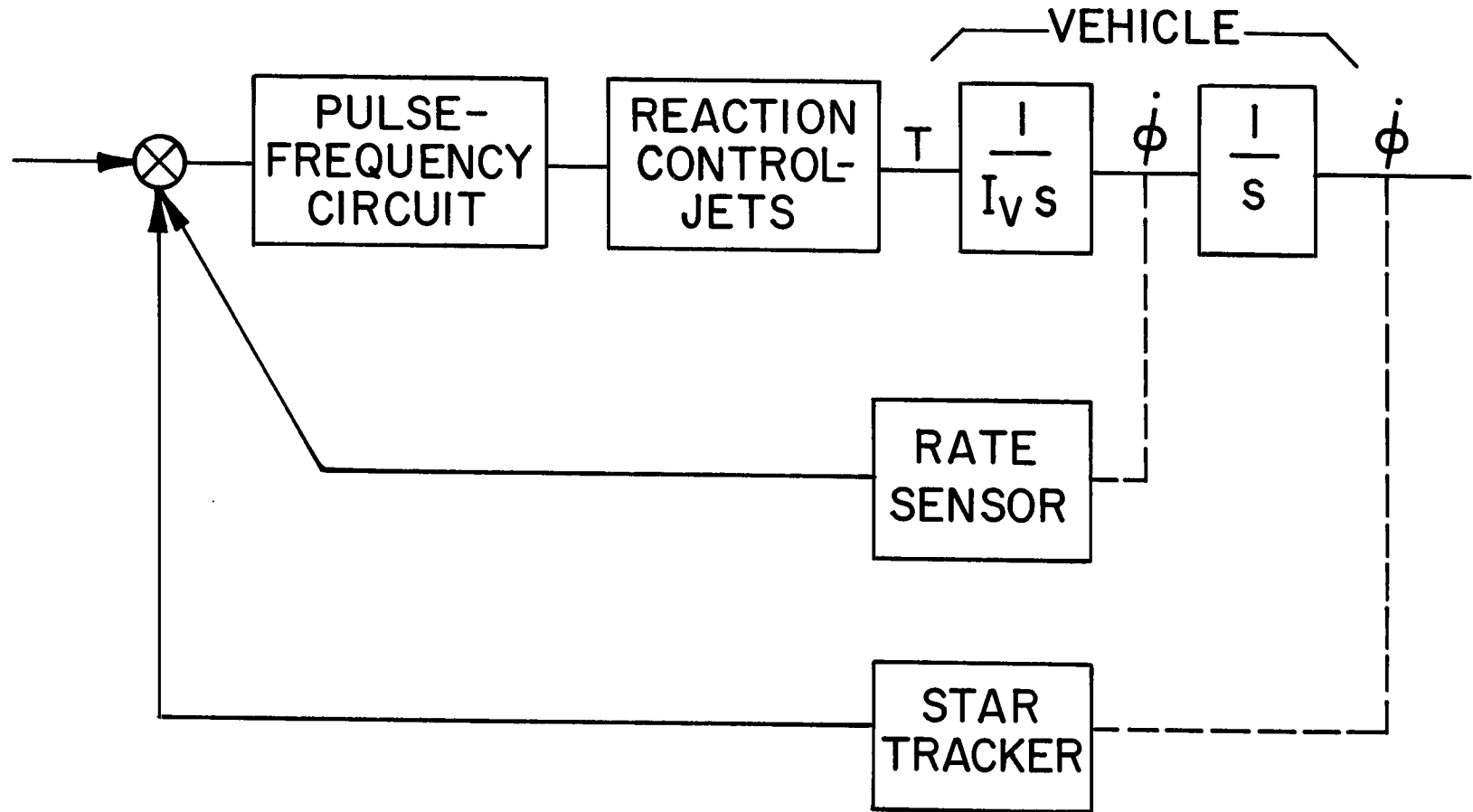


Figure 8.- Block diagram of the automatic pulse-frequency-modulated reaction-control system.

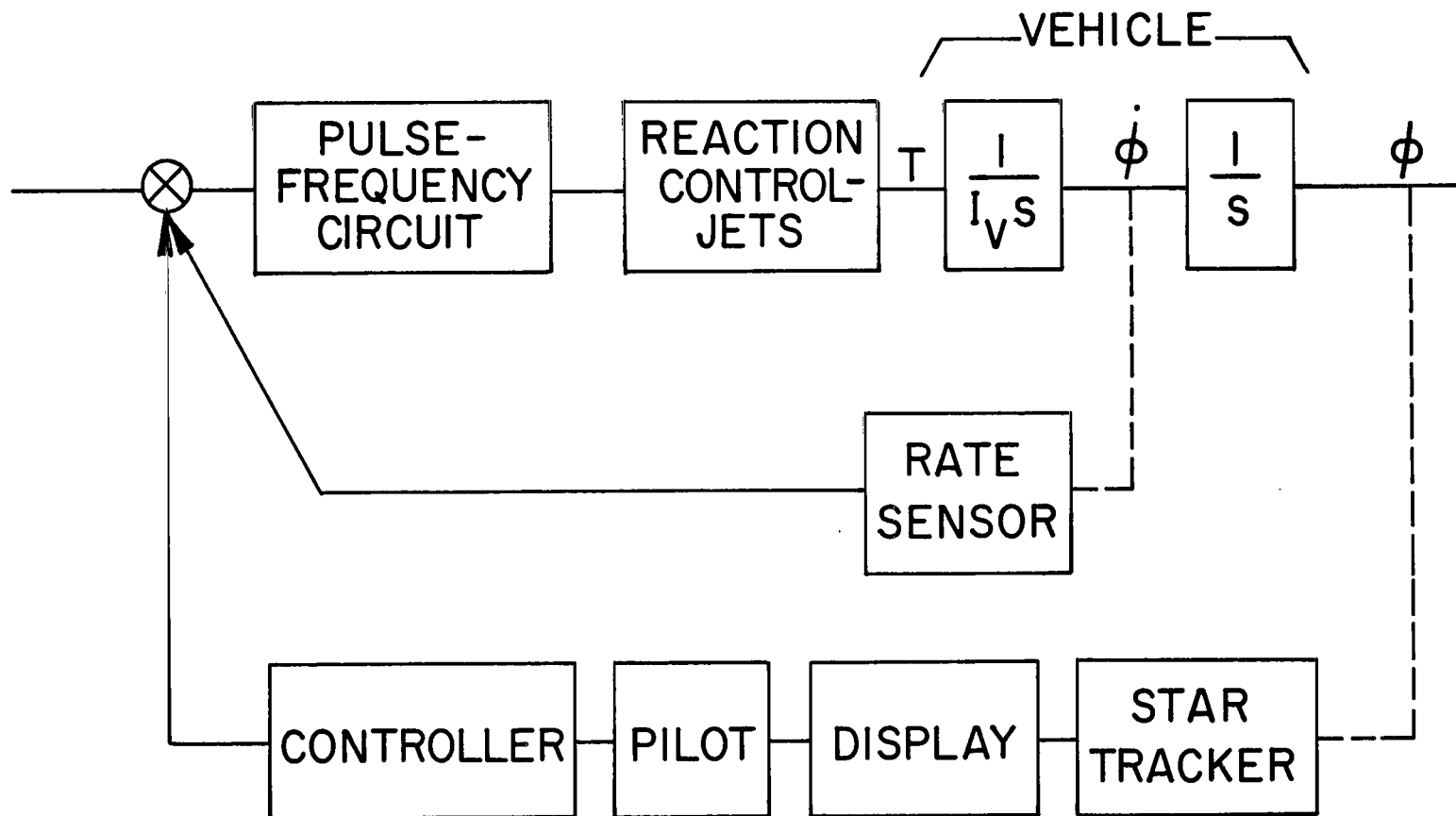


Figure 9.- Block diagram of the manually operated pulse-frequency-modulated reaction-control system.

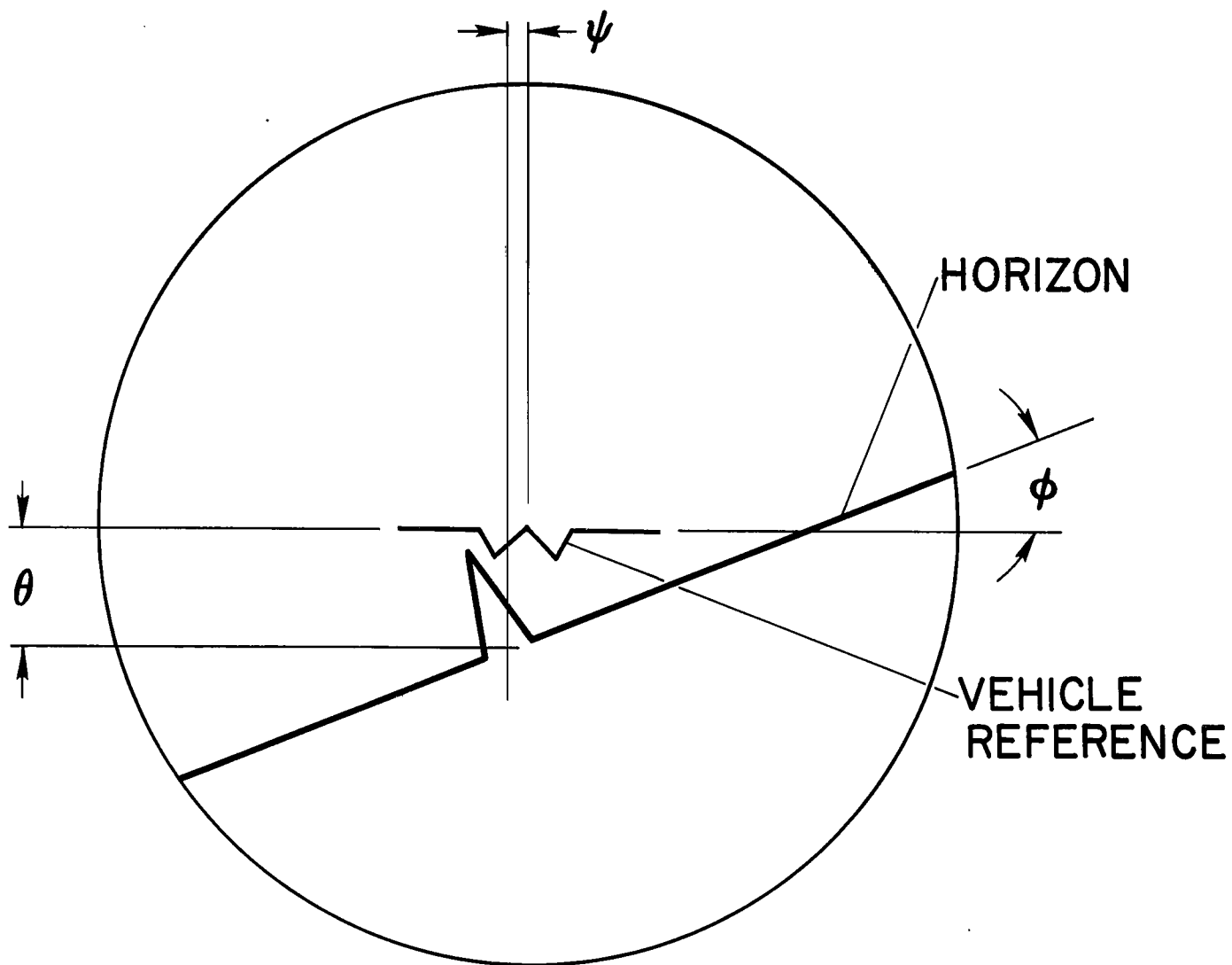
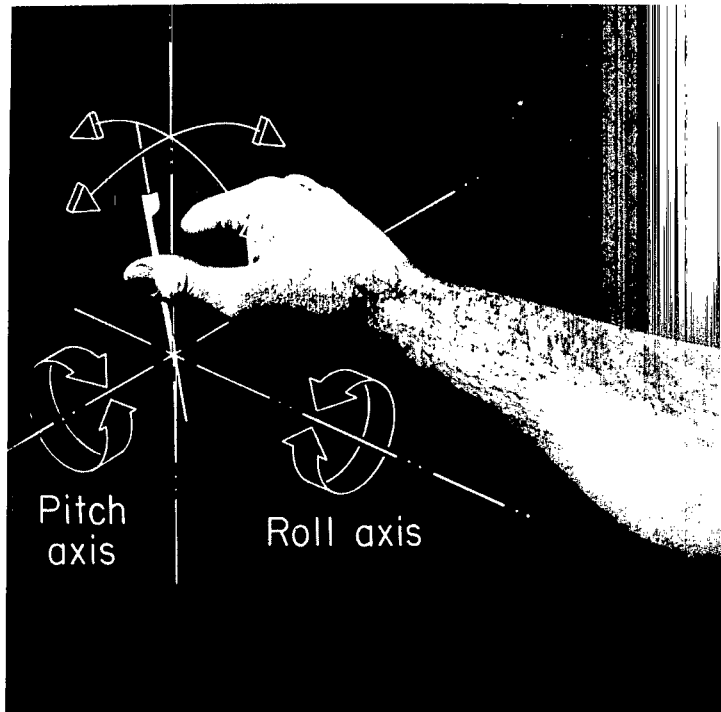


Figure 10.- Vehicle-attitude display.



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Figure 11.- Axes of rotation of the pilot controller.

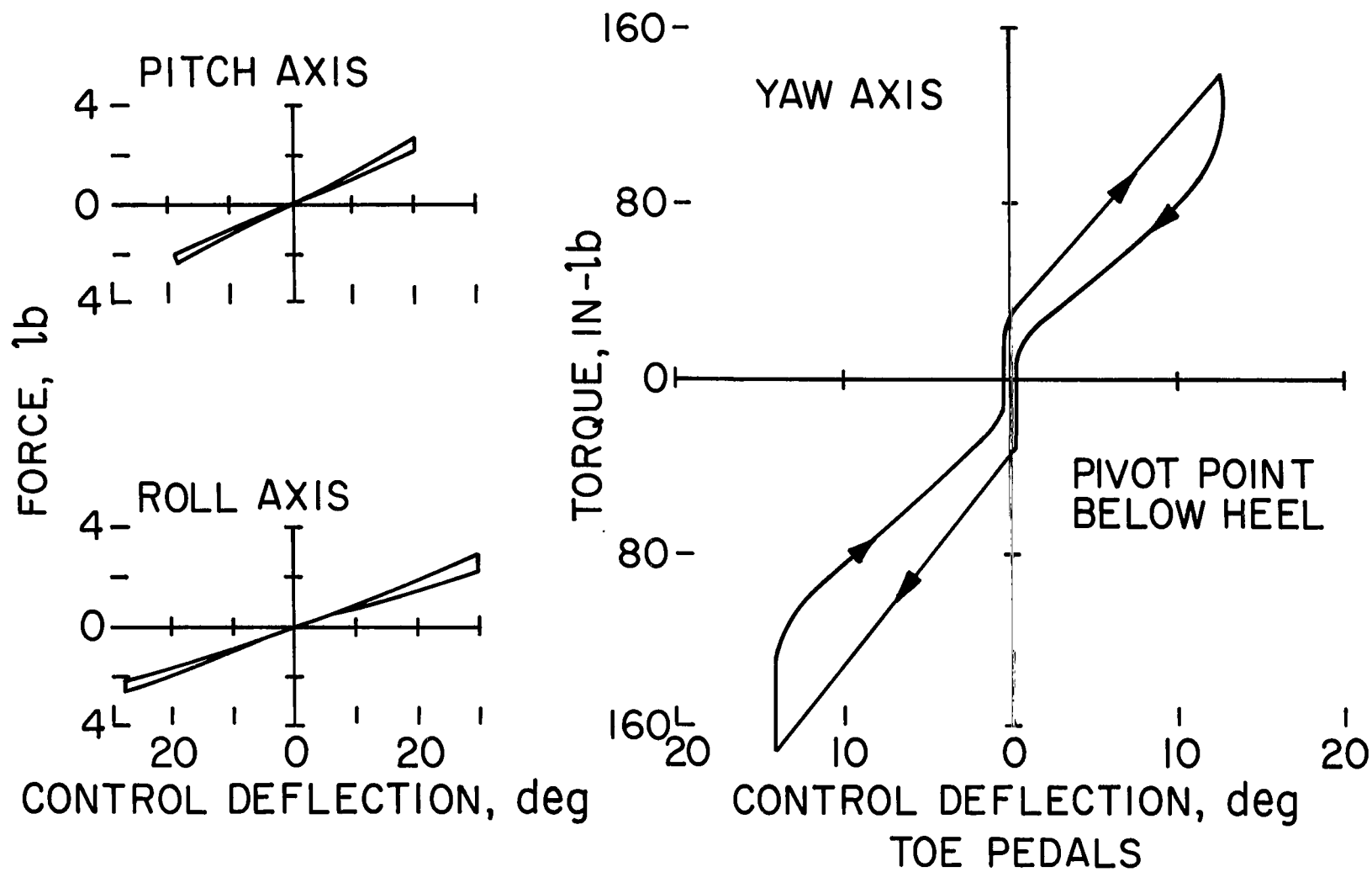
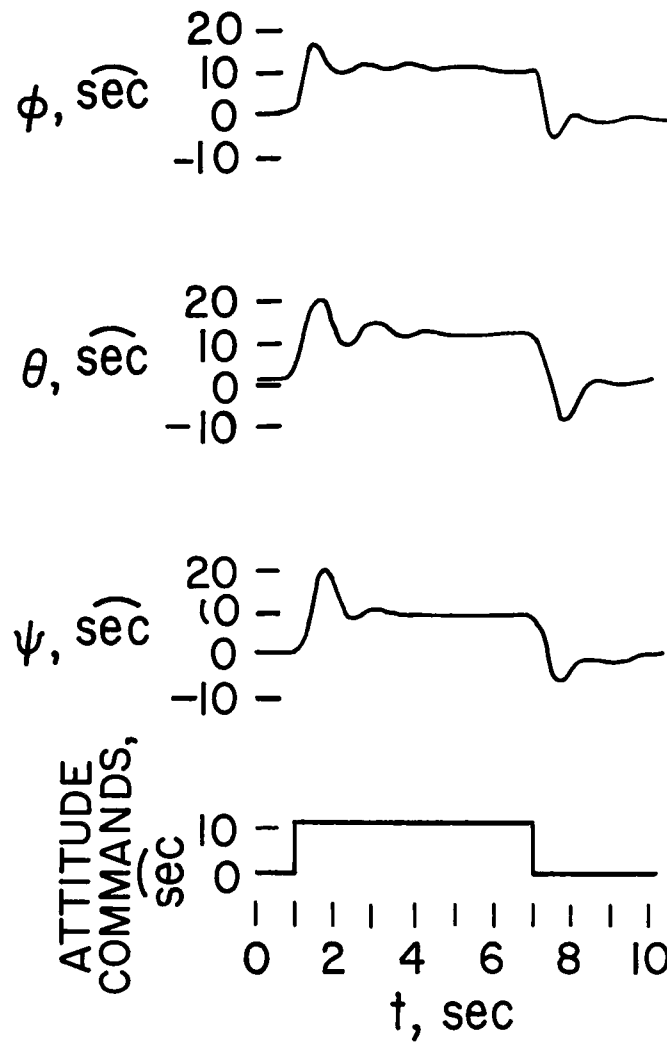
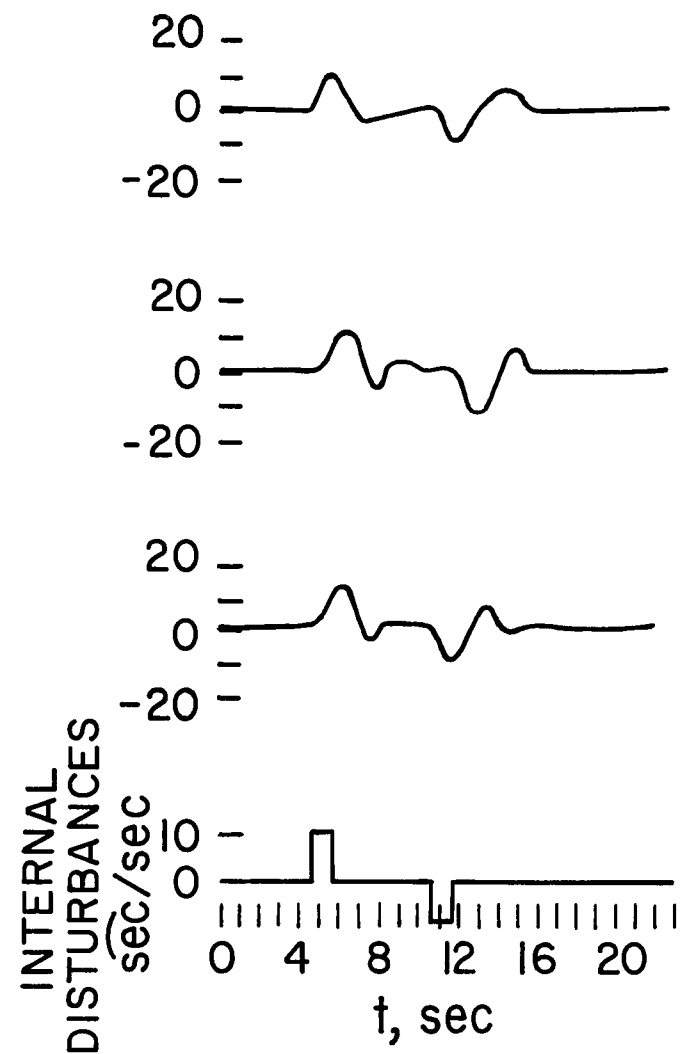


Figure 12.- Controller force-deflection characteristics.



(a) Attitude command.



(b) Disturbance.

Figure 13.- Time history of the attitude of the simulator, automatic twin-gyro control system.

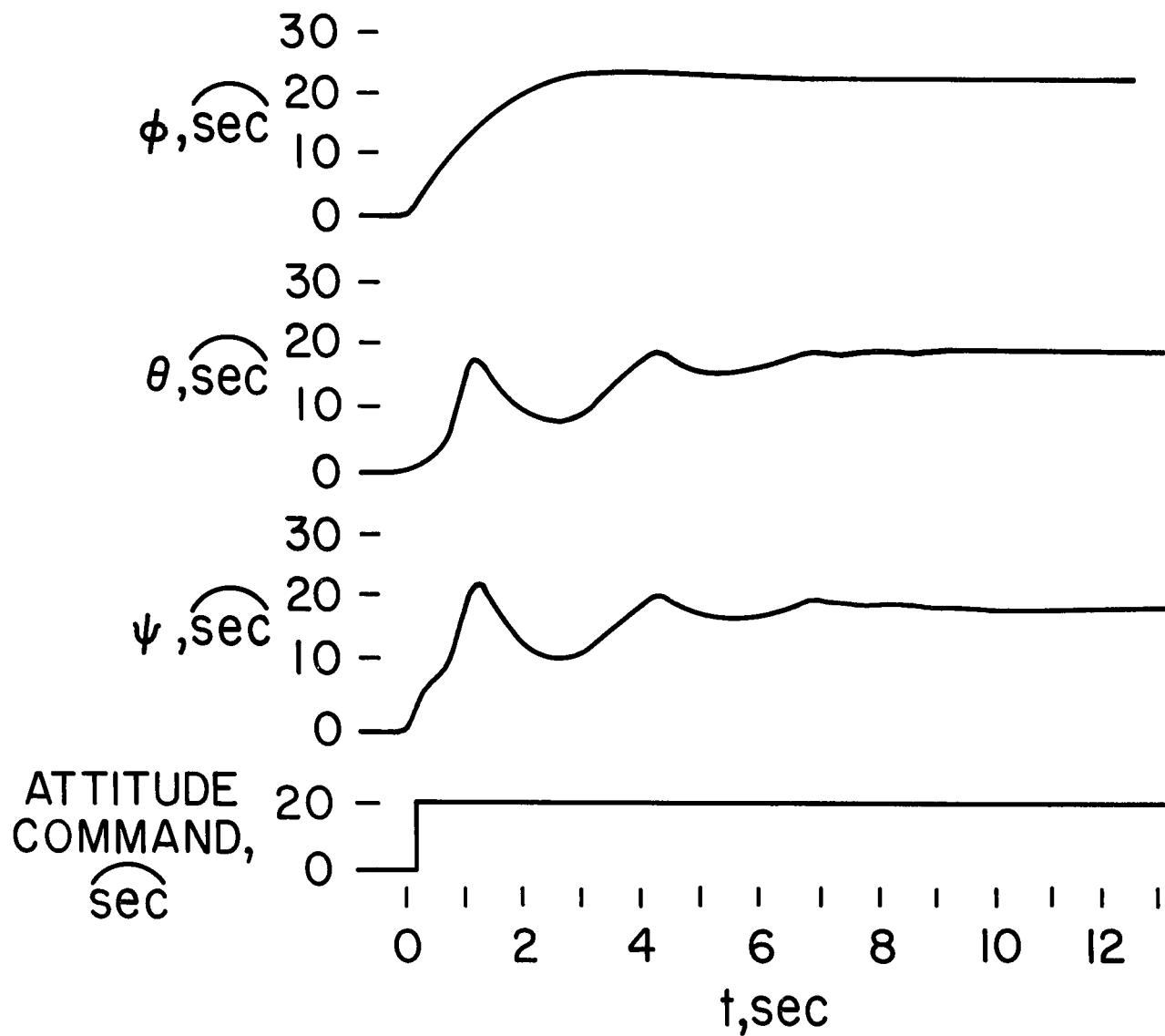


Figure 14.- Attitude response of the simulator to step commands in attitude about all axes with automatic reaction control system; $\Delta\omega = 20$ arc sec/sec.

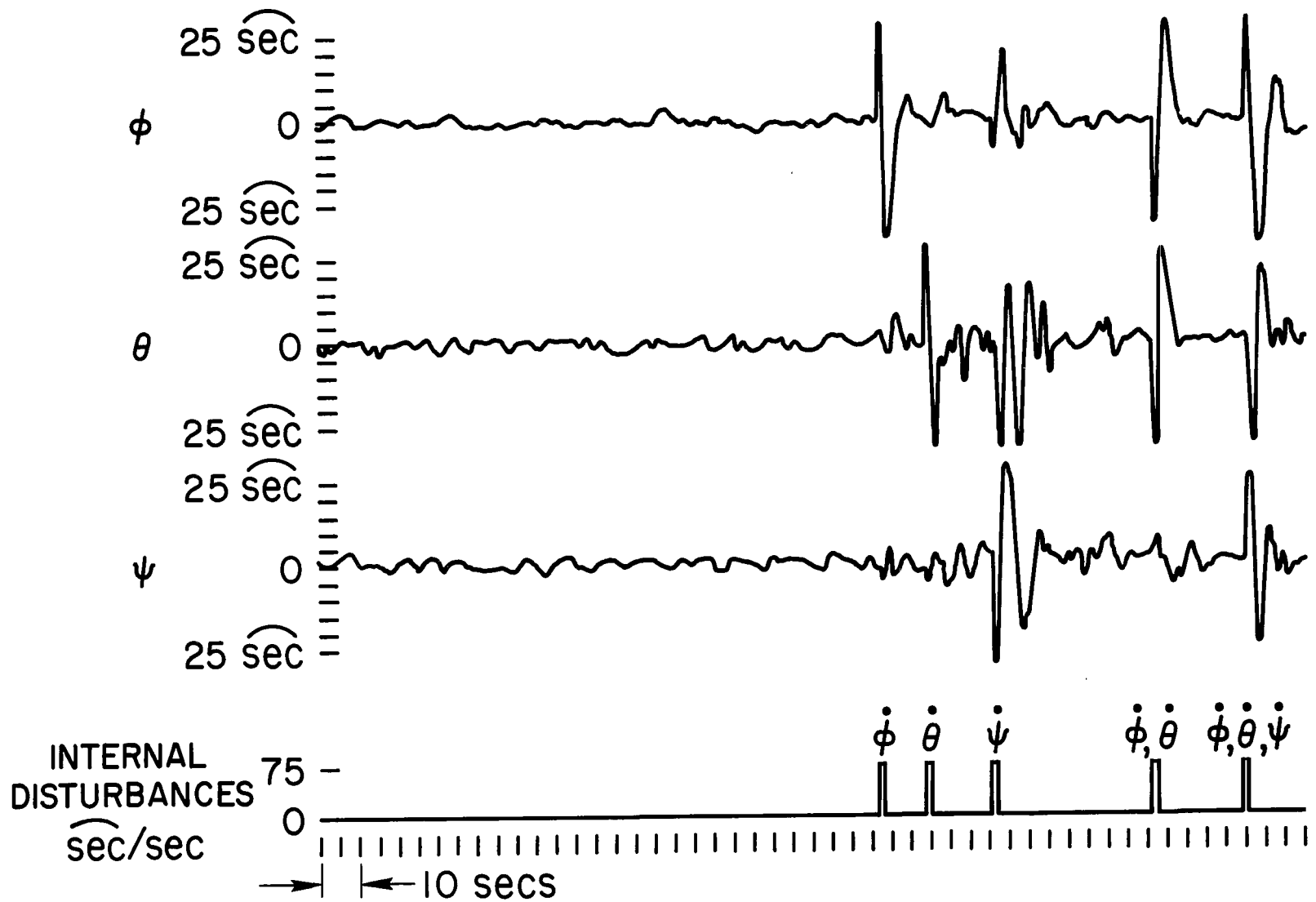


Figure 15.- Time history of the attitude of the simulator, manually operated twin-gyro control system.

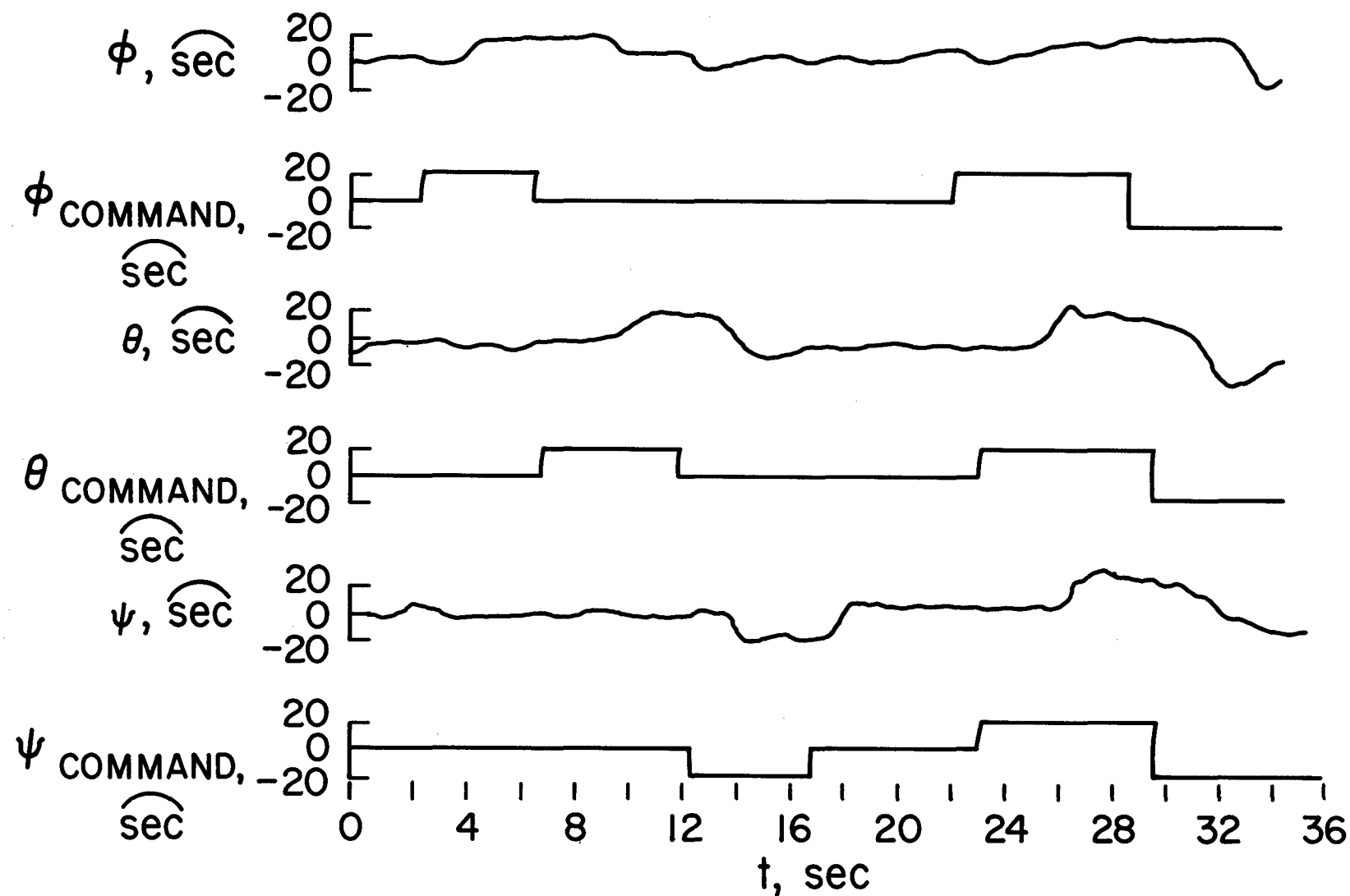


Figure 16.- Time history of attitude of the simulator, manual reaction control system with attitude commands; $\Delta\omega = 12$ arc sec/sec.

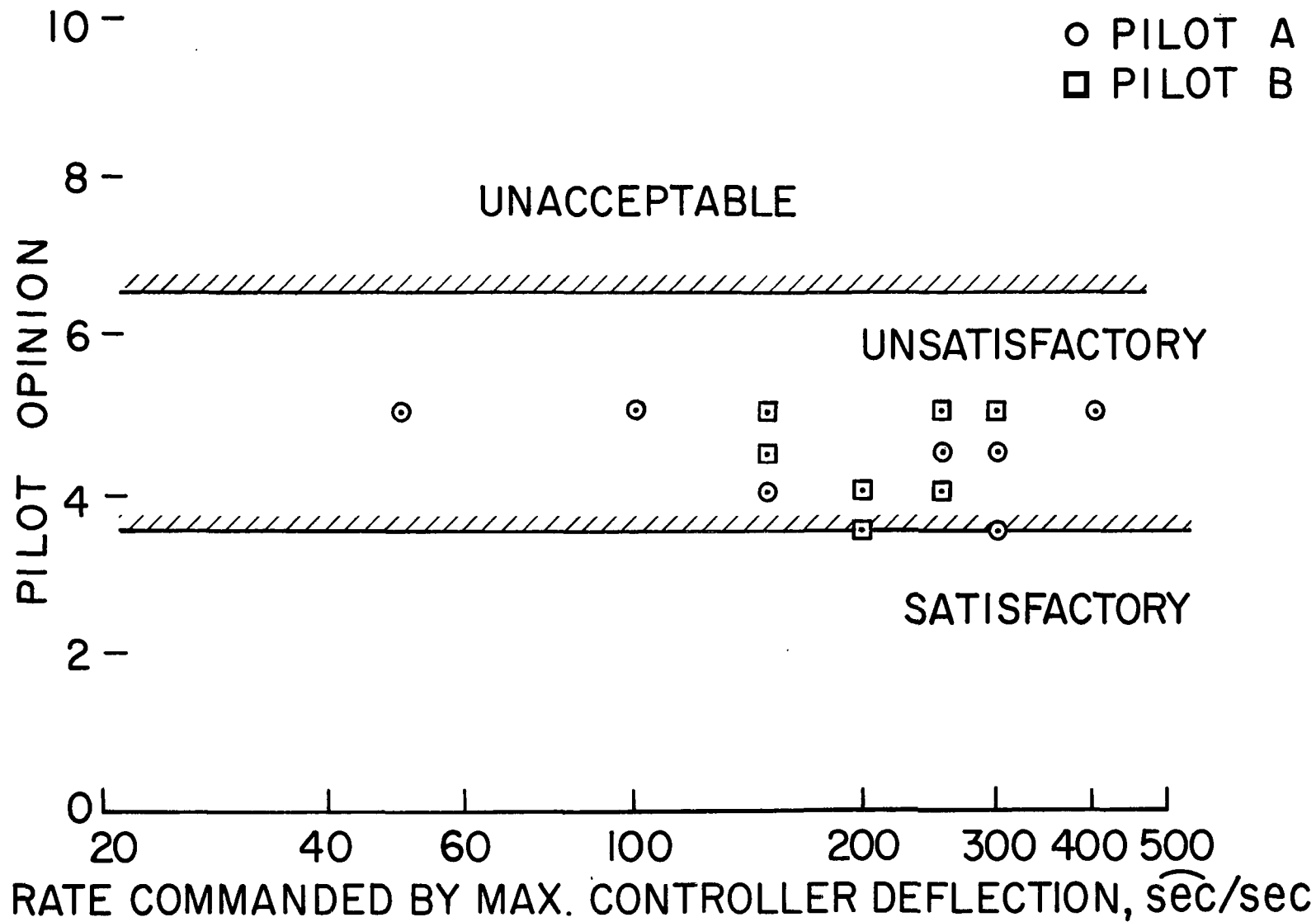


Figure 17.- Variation of pilot opinion with maximum rate command; twin-gyro control system.

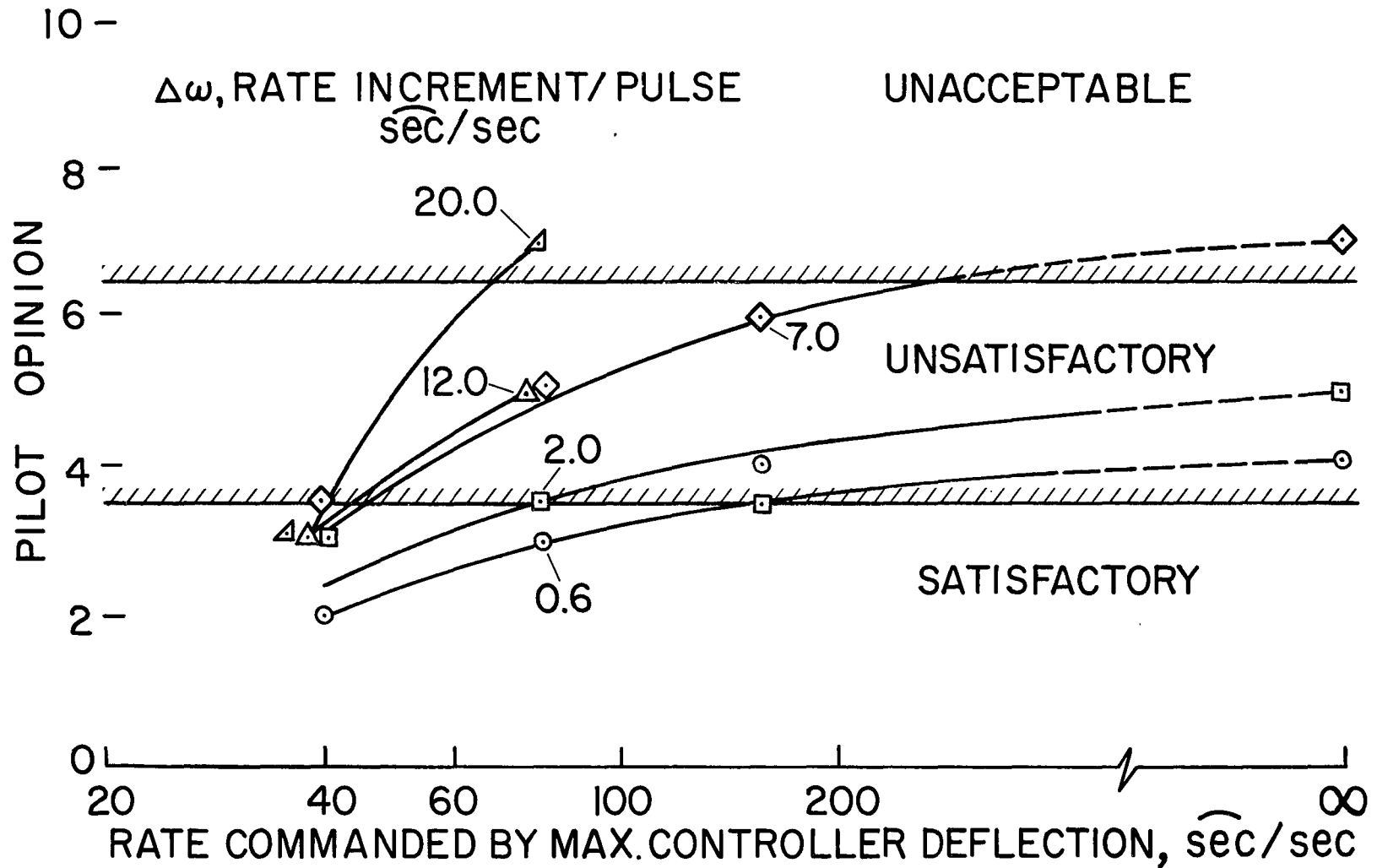


Figure 18.- Variation of pilot opinion with maximum rate command; pulse-frequency-modulated reaction control system.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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